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The Effects of a New Vector Boson on the Top Quark Cross Section at the Tevatron

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Abstract

It has recently been shown that a new neutral vector boson Z', with a mass of order 1 TeV and weak couplings to quarks only, could explain both the anomalous values of R_b and R_c and the apparent excess of large E_T jet events measured by the CDF collaboration. We calculate the effects of Z' exchange on the $t\bar{t}$ production cross section at Tevatron $p\bar{p}$ collider energies, including next-to-leading-order QCD corrections. We find a significant enhancement of the cross section and study the resulting $t\bar{t}$ invariant mass distribution, which could provide a decisive test of the Z' model.

The predictions of the Standard Model are in impressive agreement with a wide range of experimental measurements. There are, however, several cases where theory and data appear to be in disagreement: the values of R_b and R_c measured at LEP are significantly different from the Standard Model prediction [1], and there appears to be an excess of large E_T jets in the CDF data [2]. It has recently been pointed out [3, 4] that both these effects could be explained by introducing a new U(1) gauge boson (Z') of mass $O(1 \text{ TeV})$ which mixes at the 10^{-3} level with the Z^0 and has similar couplings to quarks. By assuming universal couplings to the three fermion generations, and by adjusting the couplings to the $u-$, $d-$quarks and charged leptons, the predictions for R_b and R_c can be brought into line with experiment. The additional contributions to quark–(anti–)quark scattering mediated by $s-$ and $t-$channel Z' exchange increase the predicted large E_T jet rate at the Tevatron $p\bar{p}$ collider, thus 'explaining' the recent CDF data [2].

An important feature of the Z' models of Refs. [3, 4] is that Z' vector and axial couplings to $u-$type quarks turn out to be quite large. In fact the effective $Z'u\bar{u}$ coupling is of the same order as the strong coupling: $(v'^2_u + a'^2_u)\alpha_W \sim O(10)\, \alpha_W \sim \alpha_S$, which explains why the Z' contribution to the large E_T jet cross section is comparable to the QCD contribution. Another implication of this, which is the subject of the present study, is that the top quark production cross section at the Tevatron collider (σ_t) is similarly enhanced, i.e. the model gives rise to an additional 'anomalous' contribution σ'_t from $q\bar{q} \to (Z')^* \to t\bar{t}$ which is the same order as the standard QCD contribution σ_t from $q\bar{q}, gg \to t\bar{t}$. A precise measurement of the top cross section therefore provides an important check on the model. We shall quantify this in what follows, using the same parameters as were determined in Ref. [3] from a fit to the $R_{b,c}$ and large E_T jet data.

The top cross section has been studied in the context of a variety of new physics scenarios [5], especially since the original measurement by the CDF collaboration gave a value somewhat higher than the standard QCD prediction [6]. What distinguishes the present study is that we are using a model whose parameters have already been constrained, and therefore our predictions are on a firmer footing.

Our calculations are based on the Z' model introduced in Ref. [3], where full details can be found. Only a brief summary is presented here. The neutral current sector of the electroweak Lagrangian receives an additional contribution

$$\mathcal{L}_{Z'} = \frac{e}{2\sin\theta_W\cos\theta_W}Z'^\mu\sum_f\bar{\psi}_f\gamma_\mu(v'_f + a'_f\gamma_5)\psi_f \tag{1}$$

where the vector and axial couplings are parametrized as

$$\begin{aligned}
v'_u &= x + y_u\,, & a'_u &= -x + y_u \\
v'_d &= x + y_d\,, & a'_d &= -x + y_d \\
v'_l &= v'_\nu = 0\,, & a'_l &= a'_\nu = 0\,,
\end{aligned} \tag{2}$$

with $v'_u = v'_c = v'_t$ etc. Fixing the mass of the Z' at $M_{Z'} = 1$ TeV, the parameters x, y_u and y_d can be adjusted to fit the measurements of $R_{b,c}$ while retaining the quality of the Standard Model description of other electroweak observables. The latter constraint forces the leptonic couplings to be small, and following Ref. [3] we set them to zero. A fit to

the LEP and SLC observables, including R_b and R_c, yields [3] a set of parameters which appears to be incompatible with the magnitude of the CDF jet cross section. Moving these parameters within their errors, one is able to obtain agreement with both the LEP/SLC observables and the CDF data for the following values [3]:

$$x = -1, \quad y_u = 2.2, \quad y_d = 0 , \tag{3}$$

which we will refer to as 'final fit' in the following. Note that a variation of x between -1.5 and -0.5 and of y_u between 2 and 4 yields values for observables which are still compatible with the experimental data [3].
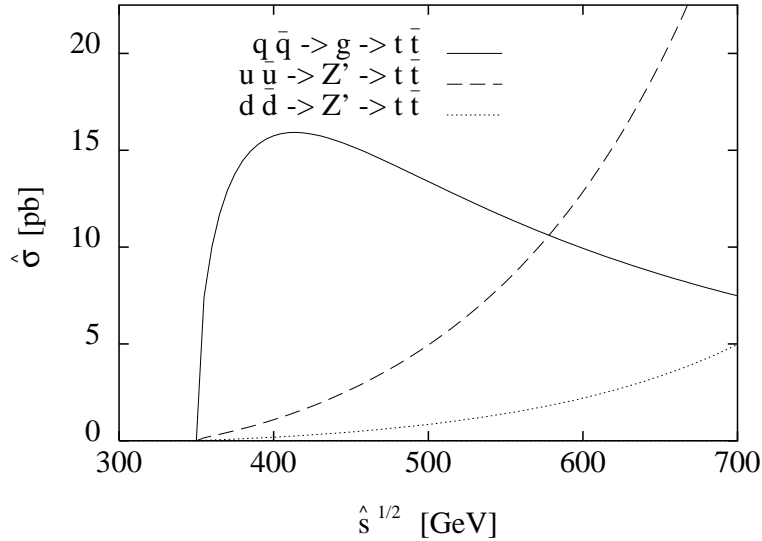

Figure 1: Parton-level cross sections for the production of a $t\bar{t}$ pair at leading order. The coupling parameters for the Z' correspond to the 'final fit' of Ref. [3].

The leading–order $t\bar{t}$ production subprocess cross sections from standard QCD and from the anomalous Z' contribution are:

$$
\begin{aligned}
\hat{\sigma}_t(q\bar{q} \to t\bar{t}) &= \frac{4\pi\alpha_S^2}{27\hat{s}} \beta(3 - \beta^2) , \\
\hat{\sigma}_t'(q\bar{q} \to Z' \to t\bar{t}) &= \frac{(G_F M_Z^2)^2}{6\pi} \frac{\hat{s}}{(\hat{s} - M_{Z'}^2)^2 + (\hat{s}\Gamma_{Z'}/M_{Z'})^2} \\
&\quad \times (v_q'^2 + a_q'^2) \left[\frac{\beta}{2}(3 - \beta^2)v_t'^2 + \beta^3 a_t'^2 \right] .
\end{aligned}
\tag{4}
$$

where $\beta^2 = 1 - 4m_t^2/\hat{s}$ and the Z' width is (for $M_{Z'} \gg m_q$)

$$\Gamma_{Z'} = \frac{G_F M_Z^2}{2\sqrt{2}\pi} 3M_{Z'} \left[v_u'^2 + a_u'^2 + v_d'^2 + a_d'^2 \right] . \tag{5}$$

2

Figure 1 displays these parton-level cross sections as a function of the subprocess centre-of-mass energy for $m_t = 175$ GeV. For the anomalous contribution, it is evident that only $u\bar{u}$ annihilation will yield a sizeable contribution to the cross section.

Our calculations of the corresponding $p\bar{p}$ cross sections use the MRS(A′) parton distributions of Ref. [7], with $\alpha_S(M_Z^2) = 0.112$. Note that approximately 90% of the QCD cross section comes from the $q\bar{q} \to t\bar{t}$ subprocess. We include also the next-to-leading-order (NLO) perturbative QCD corrections to (4). For the standard QCD $q\bar{q}, gg \to t\bar{t}$ cross sections these are taken from Ref. [8]. The NLO corrections to σ'_t factor into two pieces:

$$\sigma'_{\text{LO+NLO}} = \sigma'_{\text{LO}} \otimes K_{DY} \otimes K_{Z' \to t\bar{t}}, \tag{6}$$

where K_{DY} is the $O(\alpha_S)$ Drell-Yan correction [9] for $q\bar{q} \to Z'$ and $K_{Z' \to t\bar{t}}$ is the standard $O(\alpha_S)$ correction for the decay of a Z-like vector boson into heavy quarks [10]. Quantitatively, we observe that each of the K-factors increases the lowest-order cross section by about 15–20%. Using the 'final fit' of (3), we find at $\sqrt{s} = 1.8$ TeV and $m_t = 175$ GeV:

$$\begin{aligned}
\sigma'_{\text{LO}} &= 1.50 \text{ pb} \\
\sigma'_{\text{LO}} \otimes K_{DY} &= 1.74 \text{ pb} \\
\sigma'_t = \sigma'_{\text{LO}} \otimes K_{DY} \otimes K_{Z' \to t\bar{t}} &= 2.00 \text{ pb},
\end{aligned} \tag{7}$$

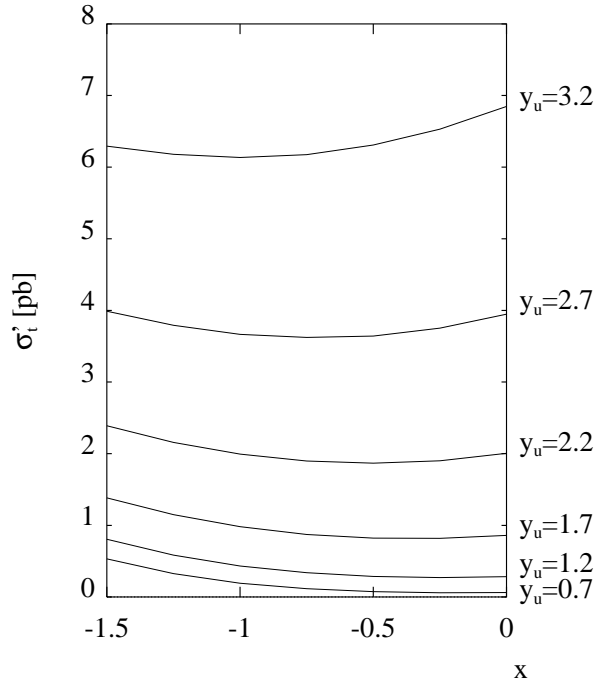to be compared to the Standard Model prediction of $\sigma_t = 4.75$ pb.

Figure 2: Variation of σ'_t with x, y_u.

The NLO σ'_t cross section, for $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV with $m_t = 175$ GeV and MRS(A′) partons [7], is shown as a function of the parameters x and y_u in Fig. 2. The

dependence on the third parameter y_d is very weak. Note that that $y_u < 2$ is disfavoured by the LEP/SLC data [3]. The relative insensitivity to the parameter x evident in the figure can be easily understood, as x enters directly in the $u\bar{u}, d\bar{d} \rightarrow Z'$ production cross sections, see Eq. (4). An increase in the production of Z' bosons is however compensated by a larger amount of Z' decays to d-type quarks. In contrast, an increase in y_u yields only an increase in $u\bar{u} \rightarrow Z'$, and correspondingly in the overall top cross section.
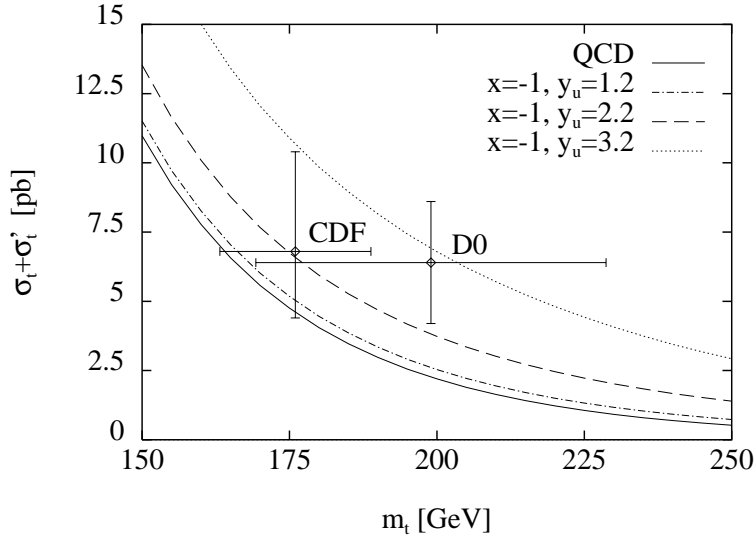

Figure 3: Predictions for $\sigma_t + \sigma_{t'}$ as a function of m_t, with data points from CDF and D0.

Figure 3 shows the total cross section $\sigma_t + \sigma'_t$ as a function of m_t at the Tevatron collider. The soild line is the standard NLO QCD prediction, the dashed line includes Z'-exchange with the 'final fit' (3) coupling parameters, and the dot-dashed (dotted) line correponds to a smaller (larger) value for the coupling parameter y_u. The data points are from CDF [11] and D0 [12]. Although the Standard Model prediction for σ_t is still within the range of the experimental errors, it can clearly be seen that the additional σ'_t contribution improves the agreement between data and theory. Furthermore, more accurate measurements of m_t and the cross section, which should become available in the near future, will provide an additional constraint on the parameter y_u.

The confirmation of an excess in the measured top cross section must of course take into account the theoretical uncertainty in the Standard Model prediction. There are three major sources of such uncertainty: unknown higher-order perturbative corrections, the value of α_S and parton distributions. A very complete study of this issue has recently been performed in Ref. [13] (see also earlier discussions in Refs. [14] and [15]). The 'best estimate' of the top cross section (at $\sqrt{s} = 1.8$ TeV) and its error from Ref. [13] is

$$\sigma_t = 4.75 \, ^{+0.63}_{-0.68} \; \text{pb} \, . \tag{8}$$

Note that the central value in (8) agrees with our result for σ_t given above. More generally, the error is approximately $\pm 15\%$ over the allowed top mass range. The important point

to note is that the 'final fit' prediction for σ'_t is about three times larger than the error on the QCD prediction.

Given the uncertainties in the standard QCD prediction and in the data, it is important to investigate other properties of the final state which could help distinguish an anomalous contribution to the cross section. Examples include the angular distributions of the top quarks and their decay products, as emphasized in Ref. [16].
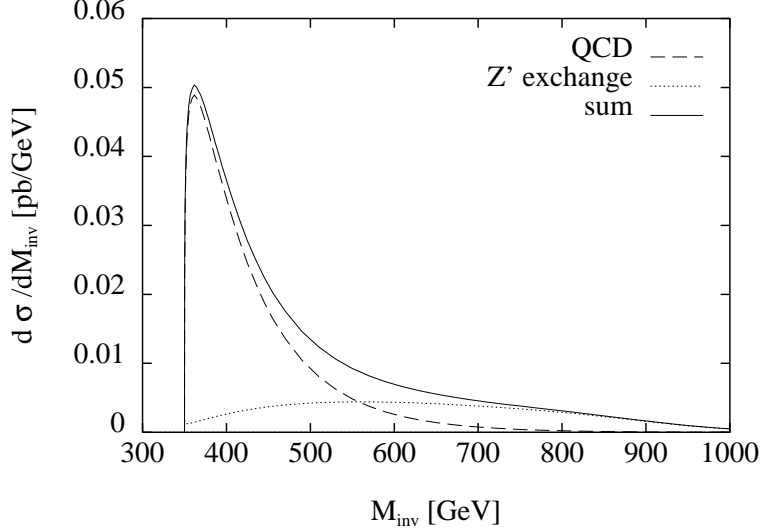

Figure 4: Invariant mass distribution of $t\bar{t}$ final states at the Tevatron.

Notice in particular that the rapidity distribution of the t quark produced in $q\bar{q} \to Z' \to t\bar{t}$ is *not* forward–backward symmetric, in contrast to the standard production mechanism. However the simplest discriminator of the anomalous and standard contributions is the distribution in the invariant mass M_{inv} of events containing $t\bar{t}$ pairs, shown in Fig. 4 for $\sqrt{s} = 1.8$ TeV, $m_t = 175$ GeV and the parameters of (3). The dashed line denotes the Standard Model prediction, the additional contribution due to the exchange of the 'final fit' Z' is indicated by the dotted line, and the solid line is the sum of these. Just as for the excess in the single jet inclusive distribution [2], the Z' contribution is visible as an enhancement of the measured cross section at large invariant masses. Note that the final-state invariant mass at next-to-leading order can include the contribution from additional gluon emission where appropriate. In practice, the invariant mass distribution of $t\bar{t}$ pairs will also depend on kinematical cuts and the jet definition used in the event reconstruction. A detailed study of these effects is beyond the scope of this work.

In summary, we have shown that the new-physics model proposed in Ref. [3] to explain the anomalies in the measurements of $R_{b,c}$ at LEP/SLC and the CDF large E_T jet cross section predicts a significant enhancement of the top quark production cross section. The 'final fit' estimate of the increase is about three times larger than the theoretical uncertainty in the standard prediction, and should be readily observable given the expected increase in the precision of the experimental measurement in the future.

Acknowledgements

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